

# SISIFO: THE OPEN-SOURCE SIMULATION TOOL OF PV SYSTEMS DEVELOPED IN PVCROPS

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**ABSTRACT:** This paper presents a description of an open-source simulation tool (features, models and calculation procedures) that has been developed under the support of the European project called PVCROPS. The main advantage of this tool is that it uses as input just parameters guaranteed by the manufacturers of the different components of a PV plant. This way, it can be used in contractual frameworks to establish the expected energy yield of a PV plant, to check the actual performance of the PV plant with quality contractual procedures linked to SISIFO, and to assign responsibilities in the case of underperformance. The tool provides, among other simulation results, the energy yield, the analysis and breakdown of energy losses, and financial analysis. Furthermore the software can generate a technical report with the results obtained in the simulation.

**Keywords:** Grid-Connected, PV System, Simulation

## 1 INTRODUCTION

The aim of this article is to introduce an open-source web simulation tool of grid connected PV systems, called SISIFO [1], which has been developed by IES-UPM, under the European project PVCROPS [2][3].

Among other features, this tool is associated with a quality control procedure, which is used to verify the technical quality and energy production of a PV plant, which may be required for project bankability [4]. SISIFO has been validated in the quality control of more than 70 PV plants with an aggregated power of more than 300 MW [5].

The following sections describe the system modelling and calculation procedures implemented in SISIFO.

## 2 INPUT DATA, ALGORITHMS AND MODELS

### 2.1 Synthetic generation of time series

SISIFO accepts as input time series of irradiance and cell temperature coming from monitoring of PV plants, meteorological stations or satellite databases. Nevertheless, there are locations where this information may be not available. In this case, the required time series may be synthesized using mathematical procedures.

For the irradiance, the available information for a location is the 12 monthly mean values of global horizontal irradiation. These data can be introduced by the user or imported from a database, like PVGIS [6].

A time series of horizontal radiation is generated using different models proposed in the literature. The recommended approach is: daily horizontal global irradiation components (beam and diffuse) are calculated using global-diffuse correlations (Page [7], Erbs [8], Macagnan [9]), and instantaneous values of beam and diffuse irradiances are calculated from the previous irradiation components (Collares-Pereira, Rabl [10]).

SISIFO also generates the horizontal time series considering different types of sky (mean, clear [11], clear and cloudy) or synthetic generation [12][13]. The tool can simulate with the previous generated data or with series from Typical Meteorological Years (TMY) [14].

To finish the calculation of the time series, the translation of irradiance values from the horizontal surface to the plane of the modules and the discount of power losses (soiling impact, shading, spectrum, etc.) are

required.

The cell temperature,  $T_c$ , is calculated from the ambient temperature,  $T_a$ , using the equation based on the nominal operation cell temperature (*NOCT*):

$$T_c = T_a + \frac{NOCT - 20}{800} G$$

Where  $T_a$  and *NOCT* (manufacturer datasheet value) are given in °C, and the irradiance,  $G$ , in W/m<sup>2</sup>.

If time series of ambient or cell temperature are not available, the simulation tool generates them from the monthly average of the minimum and maximum daily ambient temperatures [15].

### 2.2 PV generators

The maximum PV generator power,  $P_{DC}$ , is calculated using the maximum power point model:

$$P_{DC} = P^* \frac{G}{G^*} \frac{\eta}{\eta^*}$$

Where  $P^*$  is the maximum power under Standard Test Conditions (STC,  $G^* = 1000$  W/m<sup>2</sup>,  $T_c = 25$  °C, AM 1.5)  $\eta$  is the efficiency as a function of the irradiance and cell temperature, and  $\eta^*$  is the efficiency under STC,  $\eta^* = P^*/AG^*$ , where  $A$  is the effective area of the PV generator.

This model can be applied to different technologies of PV modules (Si-c, Te-Cd, Si-a and CIS). It takes into account the variation of the efficiency with the cell temperature, using the following equation:

$$\frac{\eta}{\eta^*} = 1 + \gamma(T_c - T_c^*)$$

Where  $\gamma$  is the coefficient of power variation with temperature (°C<sup>-1</sup>), which is obtained from manufacturer datasheet [16].

To refine the model, SISIFO includes the dependence of the efficiency with the irradiance, which can be accounted as follows:

$$\frac{\eta}{\eta^*} = [1 + \gamma(T_c - T_c^*)] \left[ a + b \frac{G}{G^*} + c \cdot \ln \frac{G}{G^*} \right]$$

Where the right-hand side factor is an experimental model [17], whose coefficients  $a$ ,  $b$ , and  $c$  must be fitted for each PV module. For this fitting, it is necessary to know three points of power efficiency, efficiencies at 200, 600 and 1000 W/m<sup>2</sup> obtained from the manufacturer's datasheet.

As we can see, SISIFO uses a model that simulate with parameters guaranteed by the manufacturer, which allows the assignation of responsibilities in case of underperformance.

In the simulation tool, there are available three static (ground, roof and façade) and six tracking structures (one axis horizontal, one axis vertical (azimuthal), two axis (1<sup>st</sup> vertical, 2<sup>nd</sup> horizontal), two axis (1<sup>st</sup> vertical, 2<sup>nd</sup> horizontal-venetian blind), two axis (1<sup>st</sup> horizontal, 2<sup>nd</sup> perpendicular), and two axis concentrator), with the possibility of backtracking operation [4].

### 2.3 Balance of System (BOS)

BOS components are described by general power efficiency models that are also based on datasheet information. The power efficiency of the inverter,  $\eta_i$ , is modelled using the equation [18]:

$$\eta_i = \frac{P_{AC}}{P_{DC}} = \frac{p_{ac}}{p_{ac} + (k_0 + k_1 p_{ac} + k_2 p_{ac}^2)}$$

Where  $p_{ac} = P_{AC}/P_I$ , being  $P_I$  the nominal power of the inverter and  $P_{AC}$  its output AC power, which can be determined from  $P_{DC}$  (power at the inverter input) and parameters  $k_0$ ,  $k_1$  and  $k_2$ , which must be fitted either from the power efficiency curve from experimental measurements [19] or provided by the manufacturer.

The power efficiency of the LV/MV transformer,  $\eta_T$ , is calculated as follows [20]:

$$\eta_T = \frac{P_{OUT}}{P_{AC}} = \frac{P_{OUT}}{P_{OUT} + P_{Core} + P_{Cu}}$$

Where  $P_{out}$  is transformer output power,  $P_{Core}$  are iron losses, and  $P_{Cu}$  are copper losses, which are calculated as:

$$P_{Cu} = P_{Cu,nom} \left( \frac{P_{OUT}}{P_T} \right)^2$$

Where  $P_{Cu,nom}$  are the copper losses when the transformer operates at its nominal output power,  $P_T$ .

### 3 OUTPUT DATA AND ADDITIONAL FEATURES

SISIFO provides as output data the time series of all the simulated variables, for example, meteorological parameters (extraterrestrial, horizontal, and plane-of-array radiation, ambient temperature, clearness index, air mass, etc.), geometric parameters (angle of incidence, shading factors, etc.), PV generator losses (soiling, angle-of-incidence, shading, spectrum, temperature, low-irradiance, etc.) or electrical figures (DC and AC powers, conversion efficiencies and power losses).

System performance is analyzed calculating monthly and yearly values of selected variables and usual performance indices, such as performance ratios, capture and system losses, or reference and final yields. The software also estimates the total uncertainty associated with the prediction of energy yield, using the approach

described in [21], by combining individual uncertainties in solar radiation (database uncertainty and variability of the solar resource), the simulation (transposition models from horizontal to in-plane irradiances, operating cell temperature and power response of PV generators and inverters) and performance of the PV generators (initial PV power and yearly degradation). Besides, typical confidence levels (P50, P75 and P90) are calculated, which are sometimes required for project 'bankability'.

Finally, it is worth mentioning that users have also the possibility of generating a detailed simulation report and, optionally, performing an economic and financial analysis using standard input information (initial investment, maintenance costs, feed-in-tariff, inflation, taxes, etc.).

### 4 CONCLUSIONS

An overview of the technical features of an online and free-software simulation tool of PV systems, called SISIFO, has been presented in this paper. It predicts the behaviour of different types of grid-connected PV systems using as input data time series of irradiance and temperature coming from different data resources and with any resolution. Besides, if these time series are not available, they are generated by the simulation tool.

Models of components are based on parameters guaranteed by the manufacturers or from on-site experimental measurements.

The results are displayed in tables and graphics in a technical report.

### ACKNOWLEDGEMENT

This work has been possible thanks to the funding of the FP7 European Programme (Energy) in the project PhotoVoltaic Cost reduction, Reliability, Operational performance, Prediction and Simulation (PVCROPS), Project reference 308468. ([www.pvcrops.eu](http://www.pvcrops.eu)).

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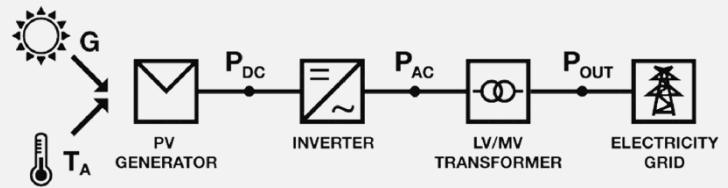


 **SISIFO:** An online simulator of PV systems

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## 1. INTRODUCTION

- Free open-source code – PHP.
- European research project PVCROPS.
- Developed by IES-UPM.



## 2. INPUT DATA, ALGORITHMS AND MODELS

- Time series of irradiance ( $G$ ) and cell temperature ( $T_c$ ). If data are not available, time series may be generated from 12 monthly mean values.
- Experimental validation of the modeling on more than 300MW.
- Models based on parameters guaranteed by the manufacturers.
- Maximum power point model:

$$P_{DC} = P^* \frac{G_{ef}}{G^*} \left[ 1 + \gamma(T_c - T_c^*) \right] \left[ a + b \frac{G_{ef}}{G^*} + c \cdot \ln \frac{G_{ef}}{G^*} \right] f_{DC}$$

### Operation conditions:

$G_{ef}$ : effective irradiance on array plane

$T_c$ : cell temperature

### Parameters guaranteed by the manufacturers:

$P^*$ : module nameplate DC power

$\gamma$ : coefficient of module power variation due to  $T_c$

$a, b, c$ : parameters related with the variation of module efficiency with  $G_{ef}$

### Baseline losses scenario:

$f_{DC}$ : other DC losses (wiring, soiling, shading...)

- Simulate different types of cell material and static and tracking/backtracking structures.

CELL MATERIAL
Si-c
Si-a
Te-Cd
CIS

STATIC	TRACKERS
Ground	One axis horizontal
Roof	One axis vertical (azimuthal)
Façade	Two axis (1st vertical, 2nd horizontal)
	Two axis (1st vertical, 2nd horizontal, Venetian blind type)
	Two axis (1st horizontal, 2nd perpendicular)
	Two axis (Concentrator)

## 3. OUTPUT RESULTS

- Tables and graphics.
- Report.
- Economic analysis.

